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(71) **Applicant** *(for all designated States except US)*: **ABB AB** [SE/SE]; S-721 83 Västerås (SE).

(72) **Inventors; and**
(75) **Inventors/Applicants** *(for US only)*: **KADDANI, Ahmed** [FR/SE]; Cedergatan 21, S-723 41 Västerås (SE). **WINDECKER, Ulrike** [DE/SE]; Stockrosvägen 17, S-722 46 Västerås (SE). **SKARIN, Dick** [SE/SE]; Styckjunkarvägen 49, S-632 36 Eskilstuna (SE). **LEMARINIER, Pavel** [FR/SE]; Regementsgatan 17, S-723 45 Västerås (SE). **ZAHRAI, Said** [SE/SE]; Cedergatan 21, S-723 41 Västerås (SE). **GU, Chun-Yuan** [SE/SE]; Flitiga Lisas väg 22, S-722 46 Västerås (SE).

(74) **Agents: FRANSSON, Henrik** et al.; ABB Group Services Center AB, Legal & Compliance/Intellectual Property, S-721 78 Västerås (SE).

(54) **Title: AN ARC WELDING METHOD**
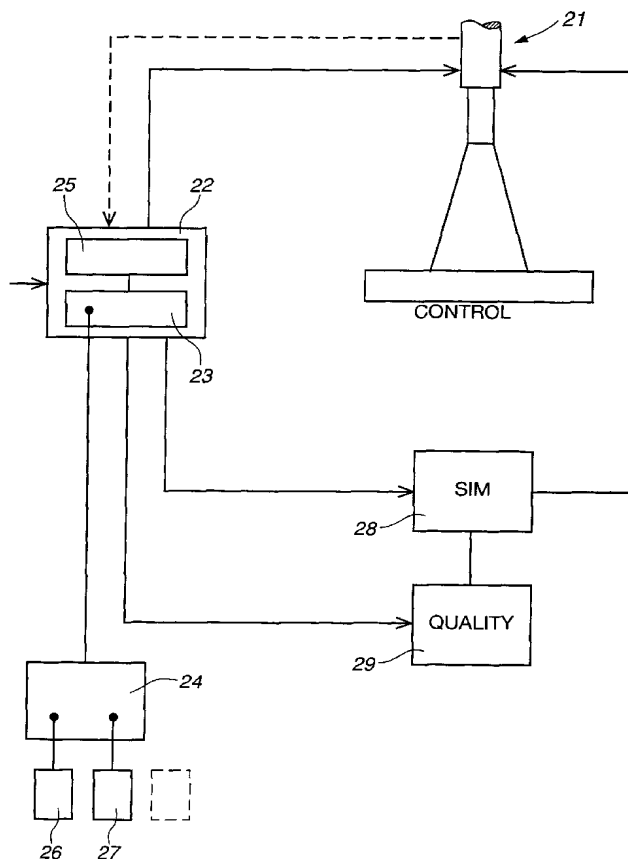
(57) **Abstract:** A method for controlling an arc welding equipment (21) used in a welding operation and adjustable by varying at least one welding parameter value, comprising the steps of determining said at least one welding parameter while using a theoretical model (24) of the welding process associated with the welding operation, and controlling the operation of the welding equipment and the welding process associated therewith by using said at least one welding parameter for adjusting the welding equipment and a device comprising an arc welding equipment (21) used in a welding operation and adjustable by varying at least one welding parameter and an arrangement (22) for controlling the operation of the arc welding equipment, said control arrangement including a means (23) adapted to determine the value of said at least one welding parameter while using a theoretical model (24) of the welding process, and a member (25) adapted to control the operation of the welding equipment and the welding process associated therewith by using said at least one welding parameter value for adjusting the welding equipment.

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AN ARC WELDING METHOD

FIELD OF THE INVENTION AND PRIOR ART

5   The present invention relates to a method for controlling an arc welding equipment used in a welding operation and adjustable by varying at least one welding parameter value, which method comprises the steps of: determining said at least one welding parameter value while using a theoretical model of the welding
10   process associated with the welding operation and controlling the operation of the welding equipment and the welding process associated therewith by using said at least one welding parameter value for adjusting the welding equipment, to a method for simulating an arc welding process which method comprises
15   the steps of: inputting data into a theoretical model representing the welding process and determining at least one welding parameter value of the welding process while using the theoretical model and the data input, with the purpose to simulate the welding process, and to a method for predicting the quality of a
20   weld obtained from an arc welding operation which method comprises the steps of: inputting data into a theoretical model representing the welding process associated with the welding operation and determining at least one property of the weld related to at least one welding parameter of the welding process
25   while using the theoretical model and the data input.

    The invention also relates to a device comprising an arc welding equipment used in a welding operation and adjustable by varying at least one welding parameter and an arrangement for con-
30   trolling the operation of the arc welding equipment, said control arrangement including a means adapted to determine the value of said at least one welding parameter while using a theoretical model of the welding process, and a member adapted to control the operation of the welding equipment and the welding process
35   associated therewith by using said at least one welding parameter for adjusting the welding equipment.

Furthermore, the invention relates to uses of the methods and to computer program products according to claims enclosed.

5   When work pieces are joined by arc welding the quality of the welded joints is strongly dependent upon the parameters set during the arc welding operation. Examples of these welding parameters are welding current, supply voltage, type of shielding gas, shielding gas flow rate, welding speed, torch angle, elec-
10   trode (wire) extension, wire feed rate, and other properties of the wire and of the work piece, such as dimensions and materials. These welding parameters interact with each other in the welding process in a complex manner and influence the properties, i.e. the geometry or type of weld, metallurgy and the me-
15   chanical strength of the weld resulting from the welding operation. More precisely, the quality of a weld joint depends strongly on the metal transfer mode present during the welding. In other words, the way metal is transferred from the wire tip (for example the anode) to the work piece (for example the cathode) dur-
20   ing the welding has a very strong effect on the final properties and the quality of the weld joint.

There is of course a need to know how different sets of the adjustable parameters will effect the properties of the weld joint,
25   so that the parameters may be adjusted in a way resulting in the weld desired. One way is to attempt to predict the metal transfer mode based on the knowledge about the influence of the different parameters. However, according to the state of art the metal transfer mode is mainly determined through empirical methods.
30   The metal transfer mode may be identified through the noise generated by the welding process by people with a very long experience in arc welding. Inspection of the weld joint after finishing the welding operation may also give clues to which metal transfer mode that was present during the welding operation.
35   Thus, at present, the settings of important welding process parameters used in robotic arc welding are found out experimen-

tally by trial and error for every single welding task or welding condition, which is both time consuming and costly. For example, in case of using parameters resulting in an undesired metal transfer mode the welded joint may be of a poor quality and the work piece may be destroyed.

One reason to the lack of knowledge about how the welding parameters effect the welding process in general, and particularly the arc, and about the relations between the welding parameters used and the quality of the weld joint, is the difficulty in making measurements of the arc, or in the vicinity of the arc, and in the near to arc regions close to the wire and the work piece. Thus, as an undesired consequence it is very difficult to design a control system based upon direct measurements of the arc parameters for controlling an arc welding equipment. The fact is that automated or robotic arc welding are used in quite few of the arc welding applications performed throughout the world today, since the difficulty in predicting the result of the welding operation and the properties of welding process associated thereto for a given set of welding parameters, together with proportionately small series of work pieces, makes it more cost efficient to perform the work manually by workers skilled in welding.

SUMMARY OF THE INVENTION

A first object of the invention is to provide a method for controlling an arc welding equipment, which method enabling that the arc welding equipment may be controlled during a welding operation by adjusting at least one welding parameter determined without the need of measurements of the welding process or repeated welding experiments prior to welding.

The first object is obtained according to the invention by providing such a method, referred to in the introduction, which comprises the steps of:

-dividing the welding process into at least two separate parts, of which at least one part represents the arc or a portion thereof, in the theoretical model,

5 -representing each of said at least two welding process parts and the welding parameter/parameters associated therewith by a model component,

-putting the model components and a model power source in an electric circuit model, and

-calculating at least one electric circuit model parameter related 10 to said at least one welding parameter from the electric circuit model.

By such a method it is possible to determine at least one welding parameter value, such as the welding current or voltage 15 supply, wire feed rate, wire extension etc., and to use this welding parameter value for controlling the arc welding equipment in accordance with the present conditions to obtain a weld with the properties desired.

20 A second object of the invention is to provide a method for simulating an arc welding process without the need of measurements of the corresponding real welding process or repeated welding experiments.

25 The second object is obtained according to the invention by providing such a method, referred to in the introduction, which comprises the steps of:

-dividing the welding process into at least two separate parts, of which at least one part represents the arc or a portion thereof, 30 in the theoretical model,

-representing each of said at least two welding process parts and the welding parameter/parameters associated therewith by a model component,

-putting the model components and a model power source in an 35 electric circuit model, and

-calculating at least one electric circuit model parameter related to said at least one welding parameter from the electric circuit model.

5   By this simulation method it is possible to obtain at least one welding parameter value, and/or the present metal transfer mode, for a given set of other welding parameters in the simulation, and for example this simulation method may be used for understanding and designing of real welding processes and for
10 default setting of welding parameters of arc welding equipment in different arc welding operations.

A third object of the invention is to provide a method for predicting the quality of a weld obtained from an arc welding opera-
15 tion without the need of repeated welding experiments.

The third object is obtained according to the invention by providing such a method, referred to in the introduction, which comprises the steps of:
20 -dividing the welding process into at least two separate parts, of which at least one part represents the arc or a portion thereof, in the theoretical model,
-representing each of said at least two welding process parts and the welding parameter/parameters associated therewith by
25 a model component,
-putting the model components and a model power source in an electric circuit model, and
-calculating at least one electric circuit model parameter related to said at least one welding parameter, and related to said at
30 least one property of the weld, from the electric circuit model.

By such a method it is possible to predict one or more mechanical properties of a weld resulting from an arc welding operation by determining one or more welding parameters required for the
35 quality desired and use this information in real arc welding operations. It is possible to use the method for predicting the qual-

ity of a weld for a given set of welding parameters as well as for determining one or more welding parameters required for obtaining certain mechanical properties of the weld.

5   According to a preferred embodiment of the invention one or more of said methods comprise the step of:
-dividing the welding process so that the arc-wire interaction region part of the welding process is separately represented by one of said model components in the electric circuit model. By
10   such a method, together with a suitable physical model, important information is obtained because it is possible to take important factors in the welding process, such as the voltage drop over the region near to anode and the heat flux from arc to anode, into consideration in determining said at least one
15   welding parameter value. In the arc-wire interaction region of the welding process, high gradients of different quantities such as temperature and concentration of particles are present, and the voltage drop in this region is very high. Thus, this region gives an important contribution to the characteristics of the
20   welding process.

      According to another preferred embodiment of the invention one or more of said methods comprise the step of:
-dividing the welding process so that the arc-work piece interac-
25   tion region part of the welding process is separately represented by one of said model components in the electric circuit model. By such a method, together with a suitable physical model, important information is obtained because it is possible to take important factors in the welding process, such as the voltage
30   drop over the region near to cathode and the heat flux from arc to cathode, into consideration in determining said at least one welding parameter value. In the arc-work piece interaction region of the welding process, high gradients of different quantities such as temperature and concentration of particles are
35   present, and the voltage drop in this region is very high. Thus,

this region gives an important contribution to the characteristics of the welding process.

According to another preferred embodiment of the invention one or more of said methods comprise the step of:
-dividing the welding process so that the arc region part of the welding process is separately represented by one of said model components in the electric circuit model. By such a method, and particularly together with an embodiment comprising the step of:
-determining said model component representing the arc region part by means of information obtained through calculations from a physical model of the arc column region part of the welding process, important information is obtained such as arc mean temperature, temperature near to the wire, temperature near to the work piece, arc radius and arc current-voltage characteristics, and it is also possible to take the thermophysical properties of a shielding gas present in the arc region into consideration in determining said at least one welding parameter value. According to another preferred embodiment of the invention one or more of said methods comprise the step of:
-determining said model component representing the arc region part by means of information obtained through calculations from a physical model of the arc-wire interaction region part and/or of the arc-work piece interaction region part of the welding process, important information is obtained because it is possible to take important factors in the welding process, such as the voltage drop over the region near to anode/cathode and the heat flux from arc to anode/cathode, into consideration in determining said at least one welding parameter value. In the arc-wire interaction region and in the arc-work piece interaction region of the welding process, high gradients of different quantities such as temperature and concentration of particles are present, and the voltage drop in these regions is very high. Thus, these regions give an important contribution to the characteristics of the welding process.

According to another preferred embodiment of the invention one or more of said methods comprise the step of:

-determining said model component representing the arc region part by means of said physical model describing the arc by at least one equation independent of the extension in space of the arc. By such a method, and particularly together with an embodiment comprising the step of:

-determining said model component representing the arc region part by means of said physical model describing the arc by said at least one equation only dependent on the time, the model component and thus said at least one welding parameter value, may be determined fast and with proportionally short computational time, which makes the method suitable to be used for example in controlling an arc welding equipment on line.

According to another preferred embodiment of the invention one or more of said methods comprise the step of:

-dividing the welding process so that the arc column region part of the welding process is separately represented by one of said model components in the electric circuit model. By such a method, together with a suitable physical model, important information is obtained such as arc mean temperature, temperature near to the wire, temperature near to the work piece, arc radius and arc current-voltage characteristics, and it is also possible to take the thermophysical properties of a shielding gas present in the arc column region into consideration in determining said at least one welding parameter.

According to another preferred embodiment of the invention said methods comprise the step of:

-dividing the welding process so that the wire part of the welding process is separately represented by one of said model components in the electric circuit model. By such a method, together with a suitable physical model, important information is obtained such as metal transfer mode, dipping frequency etc, and it is also possible to take material properties of the wire into

consideration in determining the value of said at least one welding parameter.

According to another preferred embodiment of the invention said methods comprise the step of:
-dividing the welding process so that the work piece part of the welding process is separately represented by one of said model components in the electric circuit model. By such a method, together with a suitable physical model, important information is obtained about quality features such as weld joint profile, penetration profile etc, and it is also possible to take material properties of the work piece into consideration in determining the value of said at least one welding parameter.

A fourth object of the invention is to provide a device which has an arrangement for controlling the arc welding equipment during a welding operation by adjusting at least one welding parameter determined without the need of measurements of the welding process or repeated welding experiments prior to welding.

The fourth object is obtained according to the invention by providing such a device, referred to in the introduction, in which the means included in the control arrangement is adapted to use said theoretical model comprising at least two separate parts, of which at least one part represents the arc or a portion thereof, corresponding to different parts of the welding process, each model part being represented by a model component, said model components together with a model power source being included in an electric circuit model, and adapted to calculate at least one electric circuit model parameter related to said at least one welding parameter from the electric circuit model for said control by said member. Thus, by the means according to the invention it is possible to determine how to set at least one welding parameter value, such as the welding current or supply voltage, wire feed rate, wire extension etc., with the purpose of optimizing the welding process under the present conditions,

and use this welding parameter value by said member for adjusting the arc welding equipment in accordance with the present conditions to obtain a weld with the properties desired.

5   According to a preferred embodiment of the invention said means is adapted to use said theoretical model having the arc-wire interaction region part of the welding process separately represented by one of said model components in the electric circuit model. By such a device, together with a suitable physical

10   model, important information is obtained because it is possible to take important factors in the welding process, such as the voltage drop over the region near to anode and the heat flux from arc to anode, into consideration in determining said at least one welding parameter value. In the arc-wire interaction region

15   of the welding process, high gradients of different quantities such as temperature and concentration of particles are present, and the voltage drop in this region is very high. Thus, this region gives an important contribution to the characteristics of the welding process.

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     According to another preferred embodiment of the invention said means is adapted to use said theoretical model having the arc-work piece interaction region part of the welding process separately represented by one of said model components in the

25   electric circuit model. By such a device, together with a suitable physical model, important information is obtained because it is possible to take important factors in the welding process, such as the voltage drop over the region near to cathode and the heat flux from arc to cathode, into consideration in determining said

30   at least one welding parameter value. In the arc-work piece interaction region of the welding process, high gradients of different quantities such as temperature and concentration of particles are present, and the voltage drop in this region is very high. Thus, this region gives an important contribution to the

35   characteristics of the welding process.

According to another preferred embodiment of the invention said means is adapted to use said theoretical model having the arc region part of the welding process separately represented by one of said model components in the electric circuit model. By such a device, and particularly together with an embodiment of the invention in which the means is adapted to use said theoretical model having information obtained through calculations from a physical model of the arc column region part of the welding process to be used in determining said model component representing the arc region part, important information is obtained such as arc mean temperature, temperature near to wire, temperature near to work piece, arc radius and arc current-voltage characteristics, and it is also possible to take the thermo-physical properties of a shielding gas present in the arc region into consideration in determining said at least one welding parameter. According to another preferred embodiment of the invention said means is adapted to use said theoretical model having information obtained through calculations from a physical model of the arc-wire interaction region part and/or of the arc-work piece interaction region part of the welding process to be used in determining said model component representing the arc region part, important information is obtained because it is possible to take important factors in the welding process, such as the voltage drop over the region near to anode/cathode and the heat flux from arc to anode/cathode, into consideration in determining said at least one welding parameter value. In the arc-wire interaction region and in the arc-work piece interaction region of the welding process, high gradients of different quantities such as temperature and concentration of particles are present, and the voltage drop in these regions is very high. Thus, these regions give an important contribution to the characteristics of the welding process.

According to another preferred embodiment of the invention in which said means is adapted to use said model component determined by means of said physical model describing the arc by

at least one equation independent of the extension in space of the arc, and particularly together with an embodiment of the invention in which said means is adapted to use said model component determined by means of said physical model describing

5   the arc by said at least one equation only dependent on the time, the model component and thus said at least one welding parameter value, may be determined fast and with proportionally short computational time, which makes the device very suitable to be used in controlling the arc welding equipment on line.

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According to another preferred embodiment of the invention said means is adapted to use said theoretical model having the arc column region part of the welding process separately represented by one of said model components in the electric circuit

15   model. By such a device, together with a suitable physical model, important information is obtained such as arc mean temperature, temperature near to wire, temperature near to work piece, arc radius and arc current-voltage characteristics, and it is also possible to take the thermo-physical properties of a

20   shielding gas present in the arc column region into consideration in determining said at least one welding parameter.

According to another preferred embodiment of the invention said means is adapted to use said theoretical model having the wire

25   part of the welding process separately represented by one of said model components. By such a device, together with a suitable physical model, important information is obtained such as metal transfer mode, dipping frequency etc, and it is also possible to take material properties of the wire into considera-

30   tion in determining the value of said at least one welding parameter.

According to another preferred embodiment of the invention said means is adapted to use said theoretical model having the work

35   piece part of the welding process separately represented by one of said model components. By such a device, together with a

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suitable physical model, important information is obtained about quality features such as weld joint profile, penetration profile etc, and it is also possible to take material properties of the work piece into consideration in determining the value of said at
5   least one welding parameter.

The invention also relates to computer program products according to the claims enclosed. It is obvious that the methods according to the invention defined in the sets of method claims
10   enclosed are well suited to be performed through program instructions from a processor which may be effected by a computer program.

Further advantages of and features of the methods and the de-
15   vice, the computer program products, and the uses of the methods appear from the following detailed description and the other claims enclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS
20

With reference to the appended drawings, below follows a description of preferred embodiments of the invention cited as examples.

25   In the drawings:

Fig 1 is a schematic illustration of an arc welding process,

Fig 2 is a schematic illustration of the voltage distribution in the
30   gap between a wire and a work piece in an arc welding operation,

Fig 3 is an illustration of an electric circuit model representing an arc welding process,
35

Fig 4 is a schematic illustration of a device according to the invention and of applications of the invention,

Fig 5 is a block diagram of a method according to the invention,

Fig 6 is a block diagram of another method according to the invention,

Fig 7 is a block diagram of another method according to the invention,

Fig 8 is a schematic illustration of a physical model of the arc,

Fig 9 is an illustration of the geometry of an arc defined in a physical model,

Fig 10 is an illustration of a physical model of the arc-wire interaction region in an arc welding process,

Fig 11 is an illustration of a physical model of the arc-work piece interaction region in an arc welding process,

Fig 12 is an illustration of the energy balance in the ionization zone,

Fig 13 shows different kinds of welding parameters,

Fig 14 is a schematic definition for work piece modelling of a horizontal-vertical fillet joint produced by gas metal arc welding,

Fig 15 shows an example of a non-linear regression model, and

Figs 16 and 17 are analytic models of work piece.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

In this application the wording "welding process" is used as a
5   generic term of the main parts included in an arc welding opera-
tion and of the physical processes associated therewith which
take place when an electric arc is generated between a wire
(anode) and a work piece (cathode).

10 In Fig 1 an arc welding process is schematically illustrated. The
power source 1 is connected to a wire 2 and a work piece 3 to
create a closed electric circuit by means of an arc 4 generated
in the gap between the wire 2 and the work piece 3 with the pur-
pose of transferring material from the wire 2 to the work piece 3.

15
The welding process may be divided in the following main parts:
wire part 5, arc region part 6 and work piece part 7. Further-
more, the arc region part 6 may be divided in subparts, namely
an arc-wire interaction region part 8, an arc column region part 9
20 and an arc-work piece interaction region part 10. All these parts
contribute to the characteristics of the welding process and to a
certain voltage drop in the electric circuit.

However, in the electrode regions, i.e. in the arc-wire interaction
25 region part 8 and the arc-work piece interaction region part 10 of
the welding process, the voltage drop is very high compared to
the voltage drop in the central part of the arc, i.e. in the arc col-
umn region part 9. In Fig 2 the voltage distribution along the arc,
or in other words in the gap between the wire 2 and the work
30 piece 3, is schematically illustrated. It is indicated that the volt-
age drops highly in the regions near to the wire and near to the
work piece. This means that the regions situated near to the
wire and near to the work piece are important parts in the weld-
ing process and have strong influence on the weld joint resulting
35 from the welding operation.

Furthermore, the voltage distribution in the gap is very difficult to determine by direct measuring of the arc whereas the voltage drops due to the resistances and inductances of the conduits 11 in the circuit and of the power source 1 itself are easily determi-

5   ned by conventional measurements. Thus, there is a need of a physical model for describing the phenomena of the arc to predict the behaviour of the welding process. However, as already indicated the wire 2 and work piece 3 strongly interact with the arc 4 and influence the welding process. Thus, good physical

10   models of these parts are also needed to describe the welding process in its entirety.

The main idea of the invention is to obtain the value of at least one welding parameter by means of a theoretical model and use

15   said at least one welding parameter in operating an arc welding equipment and/or in simulating an arc welding process and/or in predicting the quality of a weld obtained from an arc welding operation. This is performed by dividing the welding process into parts in a theoretical model and letting each of these welding

20   process parts and the welding parameters associated therewith be represented by a model component. The components are then put in an electric circuit model together with a model power source with the purpose of calculating at least one electric circuit model parameter related to said at least one welding pa-

25   rameter from the electric circuit model. The components may be resistive and/or inductive components, but also other electric elements than pure resistors and inductors may be included in the electric circuit model. Furthermore, the model components may be connected in series and/or in parallel.

30
In Fig 3 an example of an electric circuit model 12 including model components 13 and a model power source 14 is illustrated. In this electric circuit model 12 the wire part 5 is represented by a resistor, R_w, the work piece part 7 by a resistor, R_{wp}, and the

35   arc part 6 is represented by a resistor, R_a. In addition to these resistances it is necessary to define a model resistance R_0 and

a model inductance L_0 corresponding to the resistance and the inductance from the power source 1 itself and the cables 11 in the real welding circuit. The circuit model resistance R_0 and the inductance L_0 are well known properties, or may be chosen, and

5   for the simplification below these are treated as a single component $(RL)_{rest}$. (In this component also other resistances, such as a contact resistance between the wire and a nozzle holding the wire, may be included).

10   Although the electric circuit model 12 illustrated in Fig 3 comprises four separate components: R_w, R_{wp}, R_a and $(RL)_{rest}$, in accordance with the invention the welding process may be divided into two or more parts, but at least two separate parts, of which at least one part represents the arc or a portion thereof present

15   in the welding process. In the case of two separate model components 13 all resistances in the circuit, with the exception of the resistance R_a from the arc region part 6, are suitably included in $(RL)_{rest}$. Of course higher dissolution, i.e. more model components 13 representing different parts in the welding

20   process, gives a more precise description of the arc welding process and also the possibility to obtain information about more welding parameters and to take more characteristics of the welding process into consideration.

25   However, it is also possible to use different physical models representing subparts of a part of the welding process, the arc region part 6 for instance, which are based on the different characteristics of the part in different regions, for example the arc-wire interaction region 8, the arc column region 9 and/or the arc-

30   work piece interaction region 10, resulting in one common model component such as a resistance R_a. In this way different parts of the welding process may be described without using a separate model component 13 for each part. In addition it is also possible to use input values from other parts of the welding process when

35   the model component is calculated.

By using Kirchoff's Voltage Laws at least one electric circuit model parameter may be calculated from the electric circuit model 12. For example, if the voltage supply 14 and the other components 13 are known, the current may be calculated or vice

5   versa for a given current an unknown model component may be calculated. The model components R_w, R_a and R_{wp} in figure 3 and other such components may be calculated from one or more of the physical models of the wire, arc and the work piece and of their interaction with each other. Below, examples of physical

10   models are given.

In Fig 4 the invention and some of its applications are schematically illustrated. The device according to the invention comprises an arc welding equipment 21 to be used in a welding op-

15   eration for creating a weld joint. The welding equipment 21 are suitably an automated or robotic arc welding equipment which may be adjusted by varying at least one welding parameter, such as supply voltage, shielding gas flow rate, welding speed, torque angle, wire extension, wire feed rate etc. Furthermore,

20   the device includes an arrangement 22 for controlling the operation of the arc welding equipment 21. The control arrangement 22 comprises a means 23, for example a processor and computer programs and electric components/circuits thereto, adapted to determine the value of said at least one welding pa-

25   rameter while using a theoretical model 24 of the welding process, and a member 25, for example any kind of control equipment which is able to communicate with the welding equipment and said means and thus transfer a signal representing the welding parameter value to the welding equipment,

30   for adjusting the welding equipment 21. The adjustment may be performed prior to welding and/or on line during the welding. The means 23 is adapted to use said theoretical model 24, which comprises at least two separated parts 26, 27, of which at least one part represents the arc or portion thereof, corre-

35   sponding to different parts of the welding process. Each model part 26, 27 is represented by a model component 13, see also

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Fig 3, and these model components 13 together with the model power source 14 are included in the electric circuit model 12. The means 23 is adapted to calculate at least one electric circuit model parameter 13 from the electric circuit model 12, and to
5   use the value of this parameter related to said at least one welding parameter, for said control of the welding equipment 21 through adjusting of said at least one welding parameter of the welding process by said member 25.

10   As indicated in Fig 4 the means 23 may be used without the member 25 and the arc welding equipment 21 for other purposes than direct controlling of an arc welding equipment. Thus, such a means may be used for simulation 28 of any arc welding process and/or for prediction of the quality 29 of a weld resulting
15   from an arc welding operation.

Furthermore, said means 23 and/or the control arrangement 22 may be used in performing any of the methods described herein.

20   In Fig 5 a block diagram of the method for controlling an arc welding equipment used in a welding operation and adjustable by varying at least one welding parameter value is illustrated. The method comprises the steps of determining 30 said at least one welding parameter value while using 31 a theoretical model
25   of the welding process associated with the welding operation, controlling 32 the operation of the welding equipment and the welding process associated therewith by using said at least one welding parameter value for adjusting the welding equipment, where the determining comprises the steps of dividing 33 the
30   welding process into at least two separate parts, of which at least one part represents the arc or a portion thereof, in the theoretical model, representing 34 each of said at least two welding process parts and the welding parameter/parameters associated therewith be by a model component, putting 35 the
35   model components and the model power source in an electric circuit model, and calculating 36 at least one electric circuit

model parameter related to said at least one welding parameter from the electric circuit model.

In Fig 6 a block diagram of the method for simulating an arc
5   welding process is illustrated. The method comprises the steps of inputting 40 data into a theoretical model representing the welding process, determining 41 at least one welding parameter value of the welding process while using 42 the theoretical model and the data input, with the purpose to simulate 43 the
10 welding process, where the determining comprises the steps of dividing 44 the welding process into at least two separate parts, of which at least one part represents the arc or a portion thereof, in the theoretical model, representing 45 each of said at least two welding process parts and the welding parame-
15 ter/parameters associated therewith by a model component, putting 46 the model components and a model power source in an electric circuit model, and calculating 47 at least one electric circuit model parameter related to said at least one welding parameter from the electric circuit model.
20
In Fig 7 a block diagram of the method for predicting the quality of a weld obtained from an arc welding operation is illustrated. The method comprises the steps of inputting 50 data into a theoretical model representing the welding process associated with
25 the welding operation, determining 51 at least one property of the weld related to at least one welding parameter value of the welding process while using 52 the theoretical model and the data input, where the determining comprises the steps of dividing 53 the welding process into at least two separate parts, of
30 which at least one part represents the arc or a portion thereof, in the theoretical model, representing 54 each of said at least two welding process parts and the welding parameter/parameters associated therewith be represented by a model component, putting 55 the model components and the model
35 power source in an electric circuit model, and calculating 56 at least one electric circuit model parameter related to said at least

one welding parameter, and related to said at least one property of the weld, from the electric circuit model.

5   The methods may be used for different objects such as for predicting the metal droplet formation in an arc welding operation for a given set of welding parameters, for predicting the metal transfer mode in an arc welding operation for a given set of welding parameters, for calculating at least one welding parameter value required for obtaining a particular metal transfer
10   mode in a welding operation and/or for calculating at least one default setting value to be used for adjusting an automatic arc welding equipment prior to welding. The prediction of quality may be used for example for prediction of any mechanical property of a weld joint for a given input, i.e. set of welding para-
15   meters, or in the reverse direction for determining one or more welding parameter values for a given input, i.e. any mechanical property of a weld joint. An important application of the methods and the device according to the invention is the prediction of the characteristics of a certain welding process, and as mentioned
20   above the prediction of the metal transfer mode present during an arc welding operation, which makes it possible to predict the transfer mode as a function of a certain welding parameter, such as wire feed speed or current, and thus to predict the transition region between so called short arc and spray arc mode.
25
In different embodiments of the methods the step of dividing the welding process may include dividing of the welding process so that the arc-wire interaction region part and/or the arc region part and/or the arc column region part and/or the wire part
30   and/or the work piece part is separately represented by one of said model components 13 in the electric circuit model 12. In embodiments of the methods using an electric circuit model 12 according to Fig 3 said methods comprise the steps of dividing the welding process so that the arc region part 6, the wire part
35   5, the work piece part 7 (and the part corresponding to $(RL)_{rest}$)

each is separately represented by one of said model components 13 in the electric circuit model 12.

Furthermore, in a preferred embodiment described more in detail below, said model component, R_a, representing the arc region part is determined by means of information obtained through calculation from physical models of the arc column region part 9, the arc-wire interaction region part 8, and the arc-work piece interaction region part 10.

In Figs 8, 9, 10 and 11 an example of a physical model, including submodels, based on energy, mass and momentum equations is schematically illustrated. As indicated in Fig 8 the wire, the arc, the work piece, the arc-wire interaction and the arc-work piece interaction are taken into account.

In Fig 9 the arc column 60 is assumed to be a cylindric conductor with a mean diameter 61 and an arc expansion transition zone 62 near to the wire 63. In Fig 10 the arc-wire interaction region part of the welding process is divided into a first zone 64 nearest to the wire, called the space charge zone, and a second zone 65 nearest to the arc column, called the ionization zone, for describing the properties of the zones through different physical submodels. Also the arc-work piece interaction region part of the welding process in Fig 11 is divided into a first zone 66 nearest to the work piece, called space charge zone, and a second zone 67 nearest to the arc column, called the ionization zone, for describing the properties of the zones through different physical submodels. Below follows a more detailed description of possible physical models which may be used in connection with the invention.

PHYSICAL MODELS

Arc model

5   As already mentioned the welding process may be divided into different parts and the arc region part may be divided in subparts, namely an arc-wire interaction region part, an arc column region part and an arc-work piece interaction region part. The arc column, described in this chapter, occupies most of the
10   space between the wire and the work piece. In this region, gradients of thermodynamic variables, such as temperature and pressure, are not too high and the system is in local thermodynamic equilibrium.

15   The arc model suggested here is based on energy, mass and momentum equations. The arc current generates Lorentz forces which have an important role in the welding process. The arc is usually constricted towards the wire tip. This rises the axial component of the Lorentz force. Plasma is therefore accelerated
20   towards the work piece. The electromagnetic forces in the welding process are important both for the stabilization of the arc and for material transfer to the work piece. To be able to predict some phenomena of welding arcs, thermo-physical properties of shielding gas in the temperature range 300-30000 Kelvin are re-
25   quired. Due to arc-wire and arc-work piece interactions, the shielding gas is usually contaminated by metallic vapours, which strongly influence the physical properties of the arc.

     The structure for the arc model proposed herein is shown in Fi-
30   gure 8. This structure gives the possibility to consider the effects of the shielding gas, the wire material and the work piece material.

     According to the state of art, a detailed two-dimensional simula-
35   tion of the arc is known today. However, such a simulation requi-

res long computational time. This makes it difficult to use such a tool for controlling and monitoring the arc welding process.

5   In this application instead a fast arc model with the structure illustrated in Figure 8 and 9 is proposed. The model is based upon the following considerations:

-the arc is in local thermodynamic equilibrium,

10   -the arc is assumed to be a cylindrical conductor with a uniform temperature and a mean diameter,

-an arc expansion transition zone between the wire and the arc column is considered,

15

-the arc mean temperature and diameter are obtained from the arc energy balance and the Steenbeck minimum principle. This principle is based on the minimization of the arc power loss,

20   -thermo-physical properties are calculated in separate modules and coupled to the arc model, and

-the arc-wire interaction and the arc-work piece interaction are taken into account.

25

The energy balance of the arc is given below:

$$\underbrace{\frac{LI^2}{\sigma A}}_{\substack{\text{dissipation in}\\\text{arc column}}} + \underbrace{(V_{an}+V_{ca})I}_{\substack{\text{dissipation due to}\\\text{anode and cathode falls}}} = \underbrace{A\rho v(h-h_0)}_{\text{convection}} + \underbrace{ALU_{rad}}_{\text{radiation}} + \underbrace{Q_{A\text{-}A}}_{\text{Heat transfer Arc-Anode}} + \underbrace{Q_{A\text{-}C}}_{\text{Heat transfer Arc-Cathode}}$$

30

where L is the arc length, I denotes the electric current, σ refers
35   to the electric conductivity, A is the cross section area of the arc column, V_{an} and V_{ca} are the voltage drops in the near to anode

(wire) region and in the near to cathode (work piece) region, respectively. ρ is the gas density, h and h_0 are the specific enthalpies of the arc and the surroundings, and U_{rad} is the mean radiation density, which all are functions of the arc temperature. ν denotes the mean gas velocity. The heat transfer terms for arc-anode Q_{A-A} and arc-cathode Q_{A-C} are obtained from detailed physical models of the arc-cathode and arc-anode interactions.

Using Ampere's law and integration of Navier-Stokes equations for an incompressible flow in the expansion zone a simple equation for the mean velocity can be deduced as

$$v = C_a \frac{1}{\pi R_{Arc}} \sqrt{\frac{C_b \mu_0}{2\rho} \left(\frac{R_{Arc}^2}{R_{Wire}^2} - 1 \right)}$$

where R_{arc} and R_{wire} are the radii of the arc column and wire, respectively, and μ_0 is the magnetic field constant. Constants C_a and C_b depend on the current density profiles on the anode wire and will be derived with the help of CFD simulations and simple experiments.

The equations above together with the minimization of the power loss provide all necessary information such as arc mean temperature, arc radius and arc current-voltage characteristics.

The benefits of the proposed arc model are:

-the arc model may be executed very fastly and thus it may be used as a part of a software for performing the invention and for example be used together with a model for the arc-wire interaction so that droplet formation and transport may be predicted.

Arc-work piece interaction model

Near the electrodes, high gradients of temperature and concent-
ration of particles are present. These lead to deviations from
thermal and chemical equilibrium. It is well known that the vol-
tage drops in the near to wire region and in the near to work pi-
ece region are very high and dependent on electrode materials
and arc column plasma properties. Therefore, it is important to
take physical properties of the near electrodes phenomena for
prediction of an arc welding process into consideration. In this
section the model for the interaction between the arc and the
work piece is presented. The model is based on the following:

-the region near the work piece is divided into two zones: the io-
nization zone and the space charge zone,

-collisions between particles are negligible in the space charge
zone,

-electrons and heavy particles are considered as two fluids with
two different temperatures,

-densities of ions and electrons are equal in the ionization zone,

-densities of ions and electrons are not equal in the space
charge zone,

-the electron emission mechanism is thermo-field emission, and

-equations describing the two zones are integrated over the zo-
nes.

The inputs to the arc-work piece interaction region model are the
work piece material and the plasma properties in the arc column
region (e.g. temperature and pressure). The outputs of the model
are the voltage drop over the arc-work piece interaction region

and the heat flux from work piece to arc due to charged particles. Furthermore, there is a conductive heat flux due to neutral particles. These data are needed in the global energy balance of the arc column. The model is adapted in a way so that it may easily be coupled to the arc model described above.

The benefits of the proposed arc-work piece interaction model are:

-the model may be coupled to the arc column model and/or to the arc-wire interaction region model and allows a more complete description of the arc,

-the model gives accurate predictions of the heat flux into the work piece which is an important factor that effects the quality of the weld,

-the model predicts the rate of metal vapours from the work piece,

-the model may be executed very fastly and thus it is for instance not necessary to decrease the speed of a welding operation when using the model for controlling an arc welding operation, and

-the model considers explicitly the properties of the work piece material, for example the work function and the thermal conductivity.

For illustrating the influence of the work piece material on the arc welding process, a summary of the physics is presented in the following.

The energy flux from the plasma to the work piece is given by:

$$q = J_i \left[k \left(2T_i + \frac{T_e}{2} - 2T_w \right) + e \left(\varphi_c + E_i - \phi_{eff} \right) \right] + J_e \left(2k T_e + e \phi_{eff} \right) - J_{em} \left(2k T_w + e \phi_{eff} \right) - q_{vap}$$

5

where J_e, J_{em} and J_i are the plasma back diffused electrons current density, the emitted electrons current density and the ion current density, respectively. T_w, T_e and T_i indicate the tempe-

10   rature of the cathode wall, electrons and ions. φ_c and E_i are the voltage drop in the space charge zone and the ionization energy of gas. ϕ_{eff} is the effective work function, which is defined as the difference between the mean energy of electrons inside the metal and the mean energy of the emitted electrons just outside the

15   metal. q_{vap} is the energy flux carried away by vaporization.

The energy balance in the ionization zone may be summarized as shown in Figure 12. This figure shows that a part of the total power density, the Joule effect, received by the electron gas is

20   transferred to the heavy particles by elastic and inelastic collisions. The other part of energy is lost by radiation and by thermal flow to the cold walls.

25

According to earlier investigations of the ionization zone, the

30   main losses of electronic energy is due to ionization. Based on these results, the energy losses due to elastic collisions can be

neglected. The energy balance is simplified by integration over the zone:

$$J_{em}\left(2kT_w + e\varphi_c\right) + Joule\_effect = J_e\left(2kT_e + e\varphi_c\right) + eJ_iE + 3.2JkT_e$$

The first term on the left hand side is the flux of the electrons brought into the ionization zone by the emitted electrons accelerated in the space charge zone. The second term of the left hand side presents the work of the electric field over the electrons inside the ionization zone. The first tern on the right hand side is the energy flux carried away by the electrons leaving the ionization for the space charge zone. eJ_iE is the losses of the electron energy due to ionization. Finally, the last term on the right hand side is the energy flux carried away by electrons leaving the ionization zone for the arc column.

To be able to predict the cathode region behaviour, the current densities J_e, J_{em} and J_i are required. These current densities are obtained by detailed kinetics of particles in the space charge zone. Here only the results are given.

The ion current density and the back-diffused electron current density are given by

$$J_i = n_{i0}e\sqrt{\frac{k\left(T_i + T_e\right)}{m_i}}$$

$$J_e = \frac{n_{e0}e}{4}\sqrt{\frac{8kT_e}{\pi m_e}}\exp\left(-\frac{e\varphi_c}{kT_e}\right)$$

According to the thermionic field emission mechanism, the emitted electron current density is given by Richardson-Dushman equation with the Schottky correction.

$$J_{em} = \frac{4\pi k^2 e\, m_e}{h^3} T_w^2 \exp\left(\frac{e\phi_{eff}}{kT_w}\right)$$

5

In the above equation, h and m_e are the Planck's constant and the electron mass, respectively. The effective work function is connected to the electric field according to:

10

$$\phi_{eff} = \phi_0 - \sqrt{\left(\frac{e E_c}{4\pi\varepsilon}\right)}$$

15 where Φ_0, ε and E_C are the work function of the work piece material, the dielectric constant and the electric field strength at the cathode wall.

The electron and ion densities at the edge of the space charge
20 zone can be calculated with good approximation as:

$$n_{i0} = n_{e0} = n_{plasma} \frac{0.8}{2+\alpha}$$

where

25

$$\alpha = \left(\frac{kT_i}{m_i D_{i0} k_r n_{eq}^2}\right)^{1/2}$$

30 D_{i0} and k_r are the ion-neutral diffusion coefficient at the top of the equilibrium limit and the recombination rate.

The set of equation presented is closed and can be solved easily to predict cathode region properties or arc-work piece interaction
35 region properties in the arc welding process.

Arc-wire interaction region model

In this section the model for the interaction between the arc and
the wire (anode region) is presented. The model is based on the
5   following:

-the region near the wire is divided into two zones: the ionization
zone and the space charge zone,

10   -collisions between particles are negligible in the space charge
zone,

-electrons and heavy particles are considered as two fluids with
two different temperatures,

15

-densities of ions is much less than densities of electrons in
space charge zone,

-temperature of electrons remains constant through anode re-
20   gion,

-the voltage drop in the ionization zone is negligible, and

-no electron emission from the wire is assumed.

25

The inputs to the arc-wire interaction region model are the wire
material and the plasma properties in the arc column region (e.g.
temperature and pressure). The outputs of the model are the
voltage drop over the arc-wire interaction region and the heat
30   flux from arc to wire due to charged particles. These data are
needed in the global energy balance of the arc column. The
model is adapted in a way so that it may easily be coupled to the
arc model described above.

35   The benefits of the proposed arc-wire interaction model are:

-the model may be coupled to the arc column model and/or the arc-work piece interaction region model and allows a more complete description of the arc,

5   -the model gives accurate predictions of the heat flux into the wire which is an important factor for describing the welding process,

-the model may be executed very fastly and thus it is for in-
10   stance not necessary to decrease the speed of a welding operation when using the model for controlling an arc welding operation, and

-the model considers explicitly the properties of the wire mate-
15   rial, for example the work function.

For illustrating the influence of the wire on the arc welding process, a summary of the physics is presented in the following.

20   The total energy flux from the plasma to the wire is given by the losses from the arc due to charged particles, thermal conduction and radiation minus the heat power utilized for evaporation and radiation of the wire tip surface

25

$$\dot{Q} = \underbrace{\dot{Q}_{el} + \dot{Q}_{cond} + \dot{Q}_{rad}}_{\text{energy flux from arc}} - \underbrace{\dot{Q}_{ev,wire} - \dot{Q}_{rad,wire}}_{\text{energy flux from wire tip surface}}$$

For the energy flux of charged particles, electrons are conside-
30   red only, since the ion current density flux in the arc-wire interaction region is low compared to the electron current density flux

$$\dot{Q}_{el} = j_e \left(\frac{5k_b}{2e} T_e + V_{an} + \phi \right)$$

35

There is energy flux due to thermal energy of electrons, kinetic energy of electrons resulting from acceleration in electric field and potential energy of electrons after phase transformation on the wire surface (free to bound). j_e is the current density of the

5   electrons and T_e is the electron temperature in the arc-wire interaction region. The electron temperature is taken as the mean arc core temperature provided by the arc model. ϕ is the nominal work function of the wire surface (known), and V_{an} is the voltage drop over the anode region, which consists mainly of the voltage

10   drop in the space charge zone

$$V_{an} = \varphi_{an}$$

where j_e is obtained from kinetics

15

$$j_e = j_e(n_e, \varphi_{an})$$

where n_e is the electron density in the anode region and is calculated using the equation of state, thermodynamic equilibrium

20   laws and the thermodynamic properties of the arc (temperature, pressure).

For obtaining the voltage drop over the arc-wire interaction region the ion current density j_i is taken into account. The following

25   relation can be derived from kinetics

$$j_i = j_i(n_i, \varphi_{an})$$

where n_i is the ion density in the ionization zone, which is equi-

30   valent to the electron density n_e. Knowing the total current density j

$$j = j_e + j_i$$

35   the voltage drop over the arc-wire interaction region can be obtained.

Thermal conduction from the arc results from the temperature gradient in the anode region acting on ions, and the heat fluxes due to the kinetic energy of ions and electrons in the arc-wire interaction region

$$\dot{Q}_{cond} = \lambda \frac{\partial T}{\partial n} + n_i v_i h_i + n_e v_e h_e$$

where v_i and v_e are the velocities of ions and electrons, respectively, which are given by kinetics at thermodynamic equilibrium.

The radiation power from the arc is the fraction of the power totally radiated by the arc that reaches the wire tip surface

$$\dot{Q}_{rad} = \varepsilon_{eff} \sigma T_{arc}^4$$

where ε_{eff} is an effective emission coefficient of the arc, which can be estimated from the emission coefficient of the arc column, assuming a cylinder, times the fraction of cylinder surface directed towards the wire.

The energy flux due to evaporation of the wire tip surface is given by the product of evaporation rate and latent heat of the wire material

$$\dot{Q}_{ev,wire} = \dot{m} \Delta h$$

where the evaporation rate an may be expressed as a function of arc column pressure and wire tip surface temperature

$$\dot{m} = \dot{m}(P, T_{ans})$$

The energy flux due to radiation from the wire tip surface is given by

$$\dot{Q}_{rad,wire} = \varepsilon \sigma T_{ans}^{4}$$

The only unknown remaining is the wire tip surface temperature T_{ans}. This temperature can be obtained from the wire model. A simple estimation is that it is equal to the melting temperature of the wire material.

The set of equations presented above is closed and can be solved to predict the anode region properties or arc-wire interaction region properties in the arc welding process.

Wire model

In the arc welding process, heat transfer from the arc to the wire causes rapid formation of droplets at the wire tip. Impact of detached and transferred droplets through the arc to the work piece may result in volume deformations and alteration of the mechanical properties of the weld. In the following, a model is suggested for prediction of the mass, heat and momentum transfer from dripping droplets into the work piece.

The shape of melt metal at wire tip is influenced by time-dependent forces such as gravity, inertia, surface tension, electromagnetic force, the effect of arc pressure, viscous drag by the gas flow. An extensive description of thermophysical phenomena involved in mechanisms of formation of droplets may be formulated accurately with 2-D computer tools based on a detailed analysis of the plasma-electrode interactions in conditions of local thermodynamic equilibrium of the plasma and laminar flow in the calculation domain. However, calculations required for these op-

erations may be time-consuming and not acceptable in a user interface software to be used for controlling and/or monitoring the quality of a weld in an welding operation.

5   A simplified approach to the problem can be to consider the one-dimensional energy balance of a wire dominated by the effects of evaporation, metal transfer from the wire, ohmic heating in the wire by the arc current and current transfer from the plasma. In a quasisteady state mode, the total energy balance of

10   the wire can be written as:

$$E_v + E_m = E_{oh} + E_c$$

15   when the heat transfer processes for integrated values over the total volume of the wire stick-out are defined as:

$$E_v = \int_S q_{ev} L dS$$

20

due to the evaporation from the surface to the tip of the wire;

25

$$E_m = \rho v_0 S c \int_{T=300}^{T_{mean}} C_p dT$$

the heat losses due to metal transfer in the form of droplets detaching from the wire tips;

30

$$E_{oh} = \int_{V_w} \frac{j^2}{\sigma} d\upsilon$$

35   the heating in the wire by the arc current, and

$$E_c = \int_s \left[j_i \left(V_i - V_s + \frac{5k_b}{2e} T \right) + j_e \left(\phi + \frac{5k_b}{2e} \right) T_p \right] dS$$

5   the heat transferred from the plasma to the droplet at the tip of the wire. In the above relations, V_w is the total volume of the wire stick-out, S is the total external surface of wire, and Sc = πr^2 is the cross-sectional area of the wire at the end of the wire at z=0 (T=300 K) and r is its radius. The quantities C_p, κ and ρ are the

10 specific heat, the thermal conductivity and density of the wire material at the local wire temperature, respectively. T_{mean} is the average droplet temperature at the time of detachment, and v_0 is the wire feed speed. The evaporation rate in $g.s^{-1}$ at the wire tip is denoted as $q_{ev} = P_{ev} m_a / 4 (m_a k_b T_a / 3)^{0.5}$ where P_{ev} and m_a are

15 the vapour pressure and the atomic mass of the wire, respectively, while k_b is the Boltzmann constant and T_a the temperature of the wire surface. Other symbols are the following: L, the latent heat of evaporation of the wire material, e, the elementary charge, j_i the ion current density from the plasma, j_e the electron

20 current density from the plasma; the total current density is denoted j; T_p is the temperature immediately in front of the wire, ϕ is the nominal work function of the wire surface; σ represents the electrical conductivity, V_i is the first ionization potential of the plasma gas and V_s the voltage drop across the sheath in the wire

25 region.

In this approximation, conventional heat conduction from the plasma through neutral particles, conduction through the end of the wire and black body radiation are neglected since their effect

30 can theoretically be shown to be small compared to E_v, E_m, E_{oh} and E_e.

Heat transferred from the plasma to the wire may be expressed

35

$$S_a = j_i \left(V_i - V_s + \frac{5k_b}{2e} T_a \right) + j_e \left(\phi + \frac{5k_b}{2e} T_p \right) - q_{ev} L$$

By solving the time-dependent energy conservation equation at small time steps,

5

$$\rho\frac{\partial h}{\partial t}+\rho v_0\frac{\partial h}{\partial z}=\frac{\partial}{\partial z}\left(\kappa\frac{\partial T}{\partial z}\right)+\frac{5k_b}{2e}\left(\frac{j_z}{C_p}\frac{\partial h}{\partial z}\right)+\frac{j^2}{\sigma}+F$$

10   where F is a term referring to the heat input S_a, from the plasma, the temperature profile of the wire can be obtained, and therefore the molten length at the wire tip can be estimated as a function of time.

15   Metal transfer in the form of a droplet will occur when the molten wire reaches a critical length L_{crit} for a given set of welding parameters. Estimation of the volume of droplet can be deduced from a dynamic treatment in the wire region using simplified expressions of surface tensions, electromagnetic forces, gravity, 20   arc pressure and viscous drag force around the molten metal at the tip of the wire at each time step.

The initial shape of the electrode at a time t=0 can be taken as cylindrical with diameter equal to that of the wire covered by 25   about a 0.1 cm thick layer of molten liquid at the tip of the wire. Initial conditions are to correspond to an arc operating with continuously moving wire of undeformed cylindrical shape.

The inputs required for the wire model are the arc current, the 30   wire feed speed, the wire diameter, the initial inter-electrode separation distance, the torch angle and the characteristics of the arc. The latter may be supplied into the model by outputs from the arc model.

35   The outputs include the detachment frequency, the volume of a detached droplet of molten metal, the average temperature in a

droplet and the acceleration supported by the droplet in the axis of the arc column at detachment. This result will provide information for evaluation of reinforcement of joint for a given gas arc welding process and work piece geometry. Also available from the model will be the wire stick-out length and resistance, which allow a more accurate calculation of the arc length than from the simplified model described below.

As a first step a simplified model for the wire has been used. The arc length is obtained from a balance between wire feed rate w_{fr} and wire melting rate

$$\frac{d}{dt}\left(L + \tau\frac{dL}{dt}\right) = -w_{fr} + \frac{I^2 R_{an} + I\delta V}{\delta H}$$

where τ is a time constant that delays the change of arc length from change of heat input. The resistance of the wire stickout R_{an} is calculated assuming a constant stickout temperature

$$R_{an} = \frac{\varsigma}{A_w}(D - L)$$

where ς is the electrical resistivity of the wire, A_w the wire cross-section area, D the distance between the nozzle and the work piece. L is the arc length, which is the output of this model.

The power input considers both Ohmic heating of the wire stick-out and energy transfer from arc to wire. The wire melting rate is obtained by relating the power input to the wire enthalpy per unit length δH. The latter accounts for energy release due to electron absorption in anode and thermal energy carried by electrons

$$\delta V = \phi_{an} + \frac{5k_B T_e}{2e}$$

where ϕ_{an} is the work function of the anode material, k_B is the Boltzmann's constant, T_e is the electron temperature and e is the electron charge.

Work piece model

As part of multivariable processes, automated arc welding may be defined by so called indirect welding parameters (IWPs), acting upon a set of material parameters (MPs) with a resulting set of direct welding parameters (DWPs). IWPs should be chosen appropriately for given MPs. DWPs are to be explicitly fixed by specifications of e.g. optimal weld bead width, penetration and appearance.

A basic issue to be considered regarding control for arc welding is to determine what is to be controlled and which parameters are accessible to control actions in the process. See Figs 13 and 14.

Quality control functionalities to be implemented in the proposed software could consist of:

-process stability monitoring, i.e. high speed tracking by e.g. timedomain statistical analysis based upon measured and predicted average IWPs, for example arc voltage or current intensity. It may allow detection of disturbing inputs (anomalies in gun-to-work piece distance, insufficient shielding gas coverage, etc.). Advantageously, vision sensors and sound probes also may be used,

-quality assurance of geometry and mechanical properties of weld joints (DWPs) by process parameters setting from fast advanced physical models based on MPs and IWPs. The models may include detailed arc-work piece interactions from weld pool
5   phenomena (arc efficiency, droplet dripping, gas and impurities diffusion, etc.) and micro structural criteria (micro phases, residual stress, dislocations, etc.).

One work piece model is illustrated in Fig 17. In practice,
10   modelling of weld properties is often based on neural networks trained for a particular geometry of joints. Neural networks are parameterised non-linear regression models, see Fig 14. They can provide adapted solutions for treatment of intricate multi-variable systems when physical models are difficult to es-
15   tablish or do not exist. Also a program using neural networks should include mass, heat, and momentum transfers from the arc and dripping of droplets into work piece. Indeed, these quantities may have considerable consequences on the overall geometry of the weld and its intrinsic quality. An important component in the
20   elaboration of a neural network is the control of the characteristic magnitudes of the weights (noted $w_j^{(i)}$ in Fig 15) of input parameters. This operation requires that the network is preliminary trained from a set of known outputs when the weights are systematically changed until a best-fit description of the network is
25   obtained as a function of the inputs. Among other possibilities for modelling of the work piece, a neural network program may be trained on gravity joints obtained under specified conditions (mild steel, gas shielding, wire speed, wire feed rate, plate thickness, etc) by an arc welding robot.
30

Solidification of melt during GMA welding process depends on heat transfer conditions in the weld pool, see Fig 16. Fusion mechanism and characteristics of resultant welds are complex to model analytically. Neural networks can represent a suitable
35   alternative for a model of a workpiece.

Shape and mechanical properties of welds can strongly be af-
fected by electromagnetic forces, buoyancy forces and surface
tension forces that induce flow of molten metal in the weld pool
possibly affected by impacts of droplets, vaporization, arc pres-
5   sure and molecular contamination. Accurate enough predictions
of weld quality by analytical model of those phenomena can be
difficult to provide as they call for detailed computation and op-
timized calculation routines including appropriate numerical
methods for moving boundary systems.

10

Neural networks are powerful parameterised non-linear regres-
sion models for which no fundamental knowledge of the system
to be modelled is required. They can be generally described as
series of weighted variables (input parameters x_i)

15

$$y_j = \sum_i w_i^{(1)} x_i + \theta^{(1)}$$

20   to from arguments of non-linear regression transfer functions
(hidden variables).

Example: $h_j = \tanh y_j$

25   Since a one hidden-unit model ($h_j = h$, $y = W^{(2)}H + \theta^{(2)}$ output pa-
rameter) may not be sufficiently flexible, further degrees of non-
linearity can be introduced by combining several non-linear re-
gression transfer functions (output parameter y)

30

$$y = \sum_j w_j^{(2)} h_j + \theta^{(2)}$$

hence permitting neural networks to capture almost arbitrarily
35   non-linear relationships. The capability of neural networks to
handle complexity is much related to the number of regression

transfer functions, i.e. the number of hidden layers. An important component in the elaboration of a neural network is the control of the characteristic magnitudes of the weights ($w_i^{(j)}$) of input quantities. This operation requires that the network is preliminary

5   trained from a set of known outputs when the weights are systematically changed until a best-fit description of the network is obtained as a function of the inputs. Numerical procedures can be developed to avoid overfitting difficulties. In some cases, error estimates can also be calculated to define fitting uncertainty

10   by considering probability distributions of sets of weights instead of using a unique one.

A neural network may be produced to model effects of heat and mass transfers on weld geometry as part of an Arc Welding End-

15   user Software. However, as already mentioned, many experimental parameters can influence an arc welding process (for example wire properties, shielding gas properties, power supply, wire feed speed, welding speed, electrode extension, etc. – see figure). A systematic investigation of merely 10 parameters at

20   only three levels of variation would result in 3^{10}, i.e. about 59.10^3 possible combinations to explore. Theoretical knowledge of the arc suggests that the arc current, the welding speed and material properties are mainly responsible for heat and mass transfer into the workpiece. A GMAW process can be decomposed into sepa-

25   rate interdependent modules for, respectively, the electrical circuit, the wire (anode), the arc, for the interactions between the arc and the wire (i.e. droplet formation), the interactions between the arc and the workpiece, and the workpiece itself (cathode). The amount of welds to be produced for making a neural network

30   model of the workpiece can hence be reduced to a reasonably small number by successively comparing model results for the diverse modules to a few relevant experimental test cases characteristic of the functionality of the module tested, all critical parameters of other modules being fixed in other respects. In this

35   aim, intern resistances, inductances and resistances on the

welding equipment to be used for experiments should be meas-
ured beforehand and recording of process signals during welding
(e.g. arc current and voltage, encoding signal form wire feeding
system, etc.) should be carried out with an acquisition unit. Vali-
5   dation of module for electrical circuit can be achieved by com-
paring measured arc current and voltage with predicted values of
these quantities at different wire feed speeds and supply volt-
ages for different welding modes (short arc, spray, rapid-arc), all
other parameters being kept constant and identical between
10   models and experiments in other respects. Validation of the wire
model for simulation of mass transfer mode (i.e. droplet dripping)
can be achieved in a similar way by further measuring the aver-
age mass transfer rate from for several dimensions of wire di-
ameter. Validation of the arc model can be achieved by varying
15   supply voltage and electrode extension for different shielding
gases and wire diameters, all other parameters being kept con-
stant. Adjustments of each model may have to be implemented
stepwise during validation of each module. Eventually, experi-
ments to be carried out for modelling of complete effects of mass
20   and heat transfer into workpiece simply concern the influence of
torch and push/drag angles, welding speed, plate thickness,
plate material and joint configuration, all other aspects being
supposedly encompassed in the previously validated other rou-
tines. For maximum applicability of the software, experiments
25   shall be carried out on different joints (for example overlap, T-
joint) made e.g. in horizontal-vertical configuration of gravity
configuration or other, depending on targeted market for the
software.

30   As input from the arc-dependent models to a neural network
model of the workpiece, temperature distributions of electrons
and ions, current intensity due to both species and evaporation
rate at the workpiece surface will be accessible from a pre-cal-
culated matrix established with the validated models. Mass, heat
35   and speed of transferring droplets will also be referenced as in-

puts of the neural network from predictions obtained with the validated model for wire.

The output of the neural network should enable a determination of the weld quality as defined either by geometry or mechanical properties. A complete version of the software is to include all possible aspects of quality. When quality is associated to weld shape, the outputs will consist of geometrical dimensions of welds. A sketch of predicted weld geometry will be displayed or dimensions according to the standard EN-25817 will be listed on end-user interface. When quality is associated to mechanical properties, the outputs will consist of predicted values of e.g. yield strength, ultimate tensile strength, Charpy toughness and temper embrittlement.

Claims

1. A method for controlling an arc welding equipment used in a
welding operation and adjustable by varying at least one welding
parameter value, comprising the steps of:
-determining (30) said at least one welding parameter value
5   while using (31) a theoretical model of the welding process as-
sociated with the welding operation,
-controlling (32) the operation of the welding equipment and the
welding process associated therewith by using said at least one
welding parameter value for adjusting the welding equipment,
10   *characterized* in that it comprises the steps of:
-dividing (33) the welding process into at least two separate
parts, of which at least one part represents the arc or a portion
thereof, in the theoretical model,
-representing (34) each of said at least two welding process
15   parts and the welding parameter/parameters associated there-
with by a model component,
-putting (35) the model components and a model power source
in an electric circuit model, and
-calculating (36) at least one electric circuit model parameter
20   value related to said at least one welding parameter from the
electric circuit model.

2. A method for simulating an arc welding process, comprising
the steps of:
25   -inputting (40) data into a theoretical model representing the
welding process,
-determining (41) at least one welding parameter value of the
welding process while using (42) the theoretical model and the
data input, with the purpose to simulate (43) the welding
30   process, *characterized* in that it comprises the steps of:
-dividing (44) the welding process into at least two separate
parts, of which at least one part represents the arc or a portion
thereof, in the theoretical model,

47

-representing (45) each of said at least two welding process parts and the welding parameter/parameters associated therewith by a model component,

-putting (46) the model components and a model power source

5   in an electric circuit model, and

-calculating (47) at least one electric circuit model parameter value related to said at least one welding parameter from the electric circuit model.

10   3. A method for predicting the quality of a weld obtained from an arc welding operation, comprising the steps of:

-inputting (50) data into a theoretical model representing the welding process associated with the welding operation,

-determining (51) at least one property of the weld related to at

15   least one welding parameter of the welding process while using the theoretical model and the data input, *characterized* in that it comprises the steps of:

-dividing (53) the welding process into at least two separate parts, of which at least one part represents the arc or a portion

20   thereof, in the theoretical model,

-representing (54) each of said at least two welding process parts and the welding parameter/parameters associated therewith a model component,

-putting (55) the model components and a model power source

25   in an electric circuit model, and

-calculating (56) at least one electric circuit model parameter value related to said at least one welding parameter, and related to said at least one property of the weld, from the electric circuit model.

30

4. A method according to any of claims 1-3, *characterized* in that it comprises the step of:

-dividing the welding process so that the arc-wire interaction region part (18) of the welding process is separately represented

35   by one of said model components (13) in the electric circuit model (12).

5. A method according to any of claims 1-4, **characterized** in that it comprises the step of:
-dividing the welding process so that the arc-work piece interaction region part (10) of the welding process is separately repre-
5   sented by one of said model components (13) in the electric circuit model (12).

6. A method according to any of claims 1-3, **characterized** in that it comprises the step of:
10   -dividing the welding process so that the arc-wire interaction region part (8) of the welding process is separately represented by one of said model components (13) in the electric circuit model (12), and/or the step of:
-dividing the welding process so that the arc-work piece interac-
15   tion region part (10) of the welding process is separately repre-
sented by one of said model components (13) in the electric cir-
cuit model (12).

7. A method according to any of claims 1-6, **characterized** in
20   that it comprises the step of:
-dividing the welding process so that the arc region part (6) of the welding process is separately represented by one of said model components (13) in the electric circuit model (12).

25   8. A method according to claim 7, **characterized** in that it com-
prises the step of:
-determining said model component representing the arc region part (6) by means of information obtained through calculations from a physical model of the arc column region part (9) of the
30   welding process.

9. A method according to any of claims 7-8, **characterized** in that it comprises the step of:
-determining said model component representing the arc region
35   part (6) by means of information obtained through calculations

from a physical model of the arc-wire interaction region part (8) of the welding process.

10. A method according to claim 4 or 9, *characterized* in that it comprises the step of:
-dividing the arc-wire interaction region part (8) of the welding process into a first zone (64) nearest to the wire and a second zone (65) nearest to the arc column for describing the properties of the zones through different physical submodels.

11. A method according to any of claims 7-9, *characterized* in that it comprises the step of:
-determining said model component representing the arc region part (6) by means of information obtained through calculations from a physical model of the arc-work piece interaction region part (10) of the welding process.

12. A method according to claim 5 or 11, *characterized* in that it comprises the step of:
-dividing the arc-work piece interaction region part (10) of the welding process into a first zone (66) nearest to the work piece and a second zone (67) nearest to the arc column for describing the properties of the zones through different physical sub-models.

13. A method according to any of claims 7, 8, 9 or 11, *charac-terized* in that it comprises the step of:
-determining said model component representing the arc region part (6) by means of said physical model describing the arc by at least one equation independent of the extension in space of the arc.

14. A method according to any of claims 13, *characterized* in that it comprises the step of:

-determining said model component representing the arc region part (6) by means of said physical model describing the arc by said at least one equation only dependent on the time.

5   15. A method according to any of claims 1-14, *characterized* in that it comprises the step of:
-dividing the welding process so that the arc column region part (9) of the welding process is separately represented by one of said model components (13) in the electric circuit model (12).

10

16. A method according to any of claims 1-15, *characterized* in that it comprises the step of:
-dividing the welding process so that the wire part (5) of the welding process is separately represented by one of said model
15   components (13) in the electric circuit model (12).

17. A method according to any of claims 1-16, *characterized* in that it comprises the step of:
-dividing the welding process so that the work piece part (7) of
20   the welding process is separately represented by one of said model components (13) in the electric circuit model (12).

18. A device comprising an arc welding equipment (21) used in a welding operation and adjustable by varying at least one
25   welding parameter and an arrangement (22) for controlling the operation of the arc welding equipment, said control arrangement including a means (23) adapted to determine the value of said at least one welding parameter while using a theoretical model (24) of the welding process, and a member (25) adapted
30   to control the operation of the welding equipment and the welding process associated therewith by using said at least one welding parameter value for adjusting the welding equipment, *characterized* in that the means (23) is adapted to use said theoretical model (24) comprising at least two separate parts
35   (26, 27), of which at least one part represents the arc or a portion thereof, corresponding to different parts of the welding pro-

cess, each model part being represented by a model component (13), said model components together with a model power source (14) being included in an electric circuit model (12) and that said means (23) is adapted to calculate at least one electric

5   circuit model parameter value related to said at least one welding parameter from the electric circuit model for said control by said member (25).

19. A device according to claim 18, *characterized* in that the

10   means (23) is adapted to use said theoretical model (24) having the arc-wire interaction region part (8) of the welding process separately represented by one of said model components (13) in the electric circuit model (12).

15   20. A device according to any claims 17-19, *characterized* in that the means (23) is adapted to use said theoretical model (24) having the arc-work piece interaction region part (10) of the welding process separately represented by one of said model components (13) in the electric circuit model (12).

20

21. A device according to claim 18, *characterized* in that the means (23) is adapted to use said theoretical model (24) having the arc-wire interaction region part (18) of the welding process separately represented by one of said model components (13) in

25   the electric circuit model (12) and/or the arc-work piece interaction region part (10) of the welding process separately represented by one of said model components (13) in the electric circuit model (12).

30   22. A device according to any of claims 18-21, *characterized* in that the means (23) is adapted to use said theoretical model (24) having the arc region part (6) of the welding process separately represented by one of said model components (13) in the electric circuit model (12).

35

23. A device according to claim 22, *characterized* in that the means (23) is adapted to use said theoretical model (24) having information obtained through calculations from a physical model of the arc column region part (9) of the welding process to be

5   used in determining said model component (13) representing the arc region part (6).

24. A device according to any claims 22-23, *characterized* in that the means (23) is adapted to use said theoretical model

10   (24) having information obtained through calculations from a physical model of the arc-wire interaction region part (8) of the welding process to be used in determining said model component (13) representing the arc region part (6).

15   25. A device according to claim 19 or 24, *characterized* in that the means (23) is adapted to use said theoretical model (24) having the arc-wire interaction region part (8) of the welding process divided into a first zone (64) nearest to the wire and a second zone (65) nearest to the arc column for describing the

20   properties of the zones through different physical submodels.

26. A device according to any claims 22-24, *characterized* in that the means (23) is adapted to use said theoretical model (24) having information obtained through calculations from a

25   physical model of the arc-work piece interaction region part (10) of the welding process to be used in determining said model component (13) representing the arc region part (6).

27. A device according to claim 20 or 26, *characterized* in that

30   the means (23) is adapted to use said theoretical model (24) having the arc-work piece interaction region part (10) of the welding process divided into a first zone (66) nearest to the work piece and a second zone (67) nearest to the arc column for describing the properties of the zones through different physical

35   submodels.

28. A device according to any of claims 22, 23, 24 or 26, *characterized* in that the means (23) is adapted to use said model component determined by means of said physical model describing the arc by at least one equation independent of the extension in space of the arc.

5

29. A device according to claim 28, *characterized* in that the means (23) is adapted to use said model component determined by means of said physical model describing the arc by said at least one equation only dependent on the time.

10

30. A device according to any of claims 18-29, *characterized* in that the means (23) is adapted to use said theoretical model (24) having the arc column region (9) part of the welding process separately represented by one of said model components (13) in the electric circuit model (12).

15

31. A device according to any of claims 18-30, *characterized* in that the means (23) is adapted to use said theoretical model (24) having the wire part (5) of the welding process separately represented by one of said model components (13) in the electric circuit model (12).

20

32. A device according to any of claims 18-31, *characterized* in that the means (23) is adapted to use said theoretical model (24) having the work piece part (7) of the welding process separately represented by one of said model components (13) in the electric circuit model (12).

25

30   33. A use of a method according to claim 2, or according to claim 2 and any of claims 3-17, for predicting the metal droplet formation in an arc welding operation for a given set of welding parameters.

35   34. A use of a method according to claim 2, or according to claim 2 and any of claims 3-17, for predicting the metal transfer

mode in an arc welding operation for a given set of welding parameters.

35. A use of a method according to any of claims 1-17 for calculating at least one welding parameter value required for obtaining a particular metal transfer mode in a welding operation.

36. A use of a method according to any of claims 1-17 for calculating at least one default setting value to be used for adjusting an automatic arc welding equipment prior to welding.

37. A computer program product for operating a method according to any of claims 1-17.

38. A computer program product comprising code means and/or software code portions for enabling a processor to perform the steps of any of claims 1-17.

39. A computer program product for operating a device according to any of claims 18-32.

40. A computer program product according to any of claims 37-39 provided at least partially through a network such as Internet.

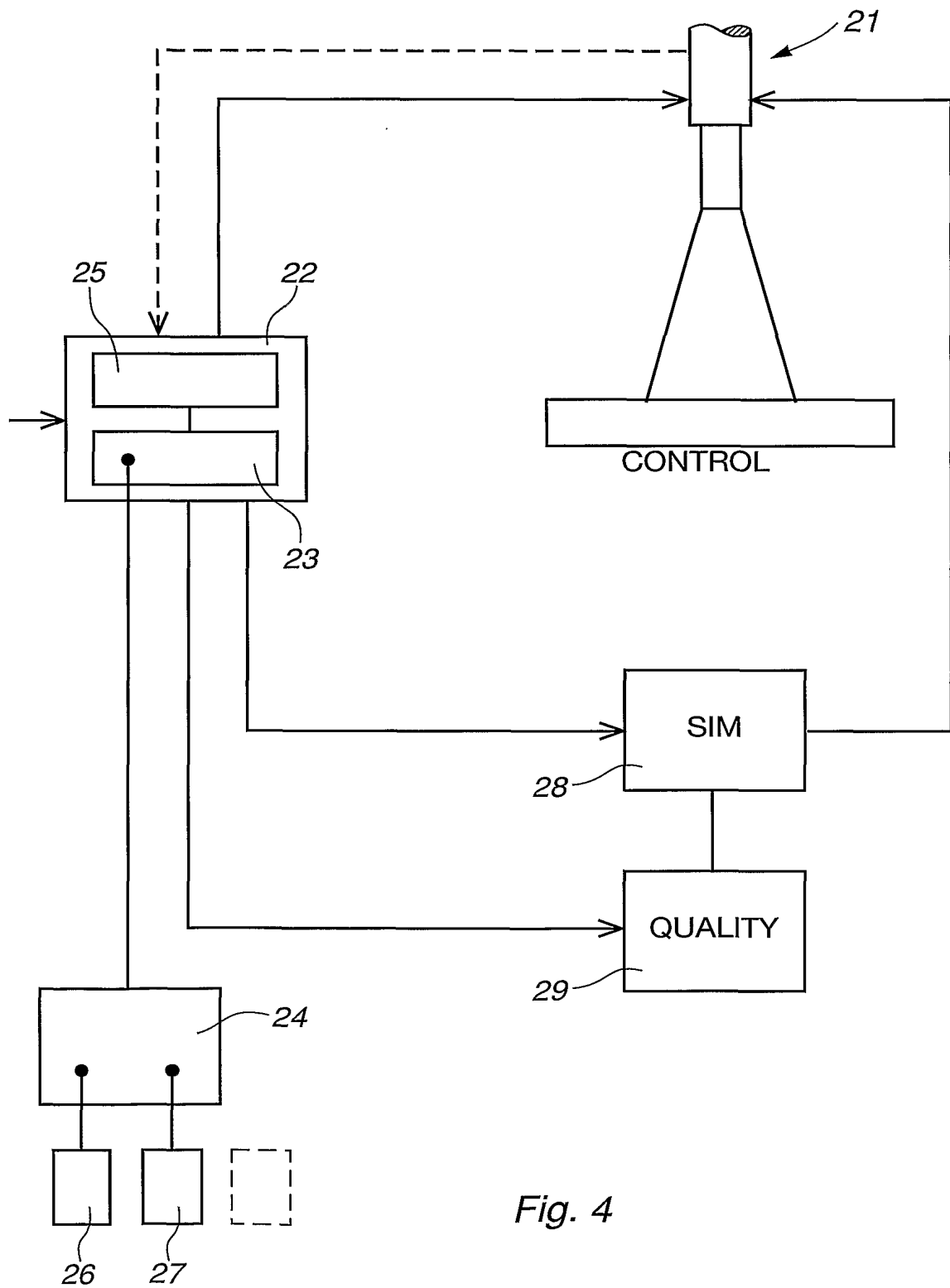41. A computer readable medium containing a computer program product according to any of claims 37-40.
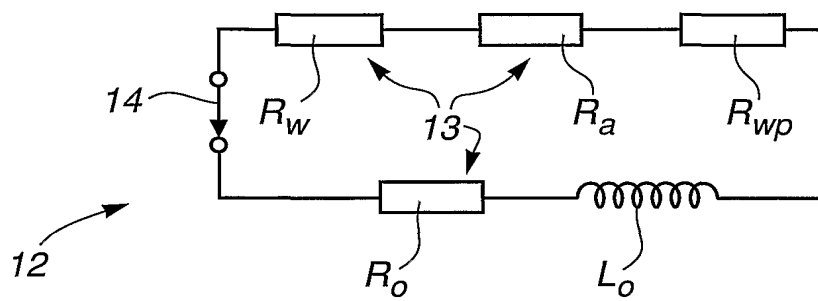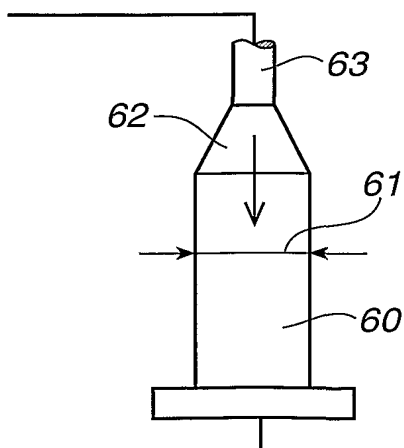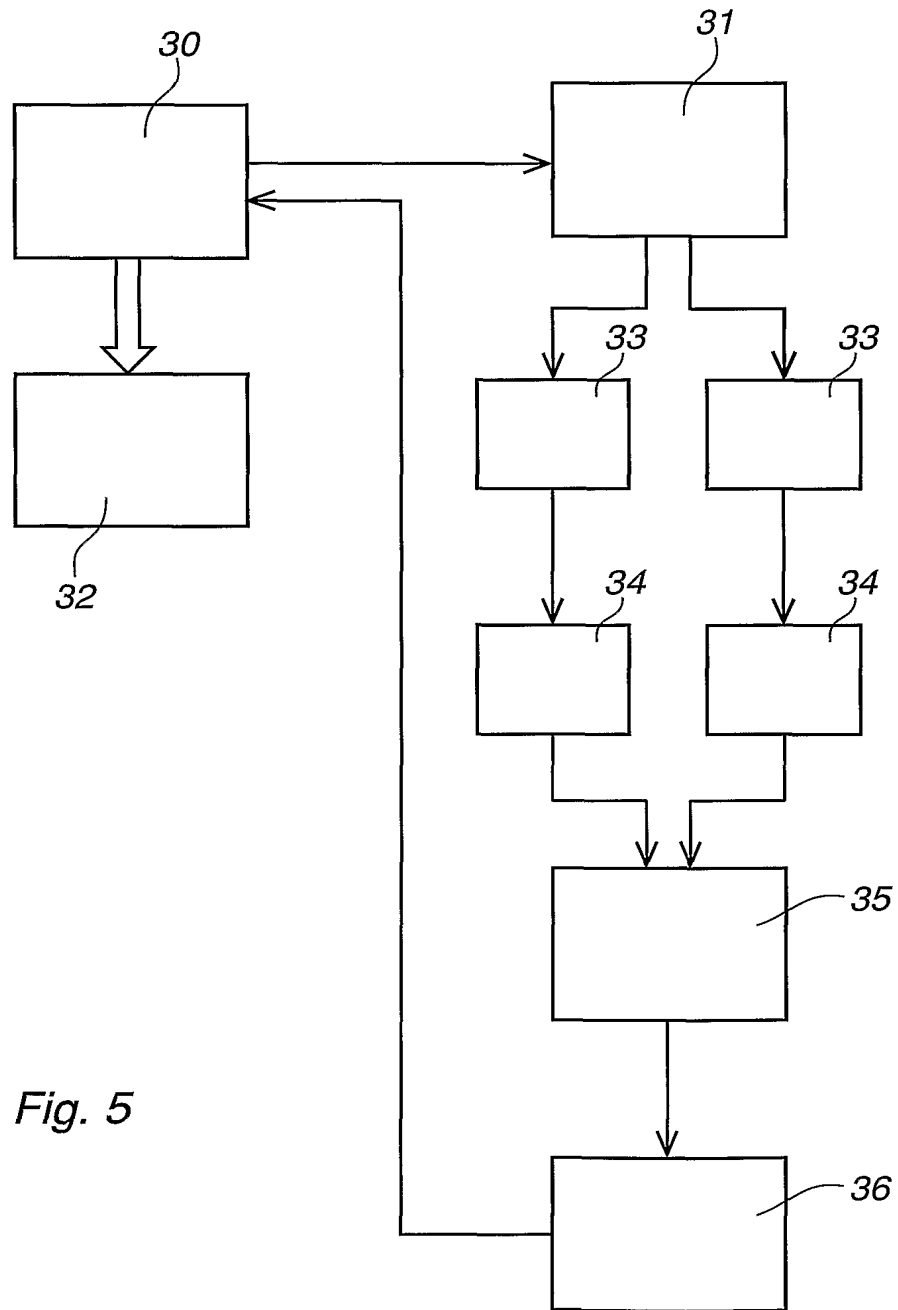
Fig. 1

Fig. 2

Fig. 4

3/11
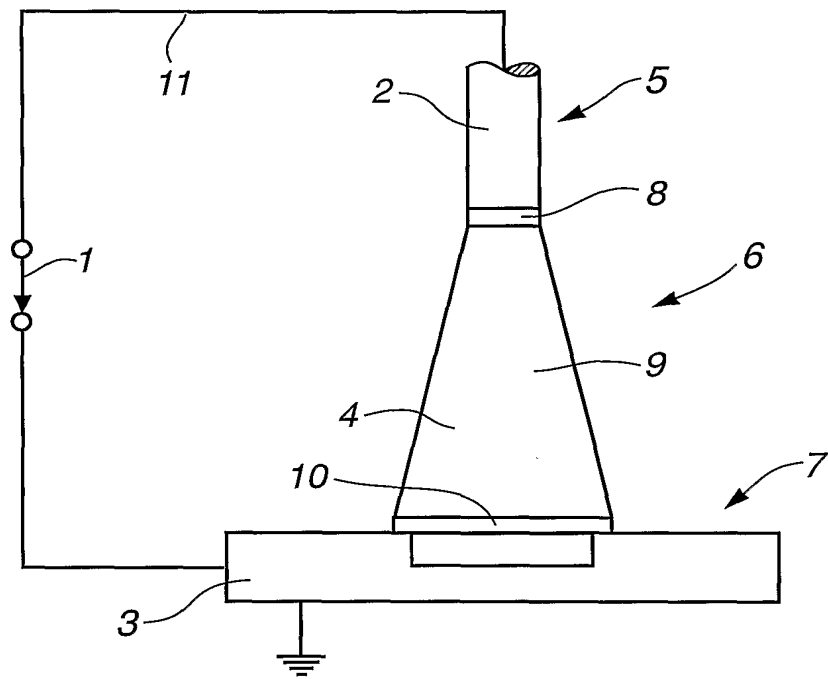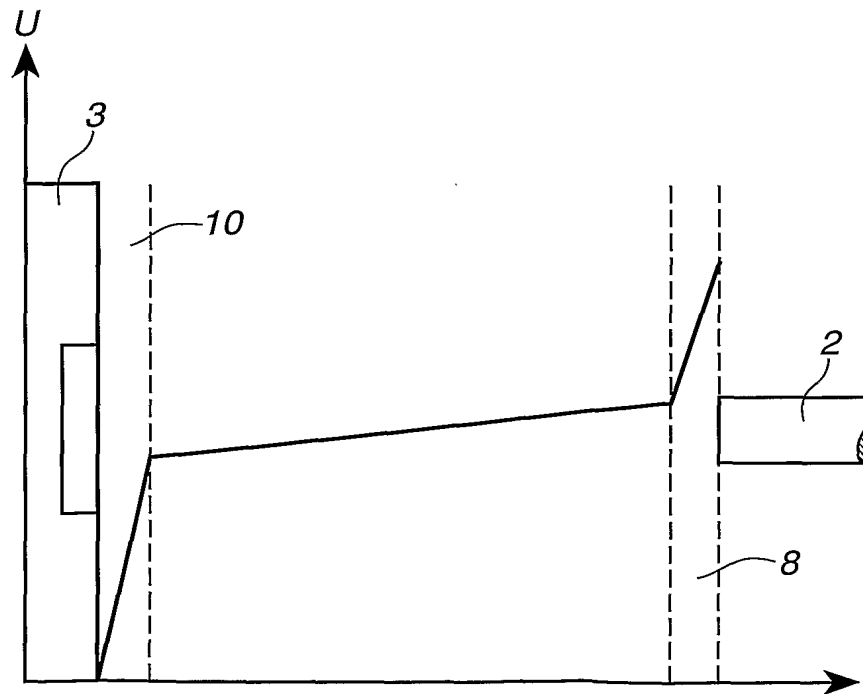
Fig. 3
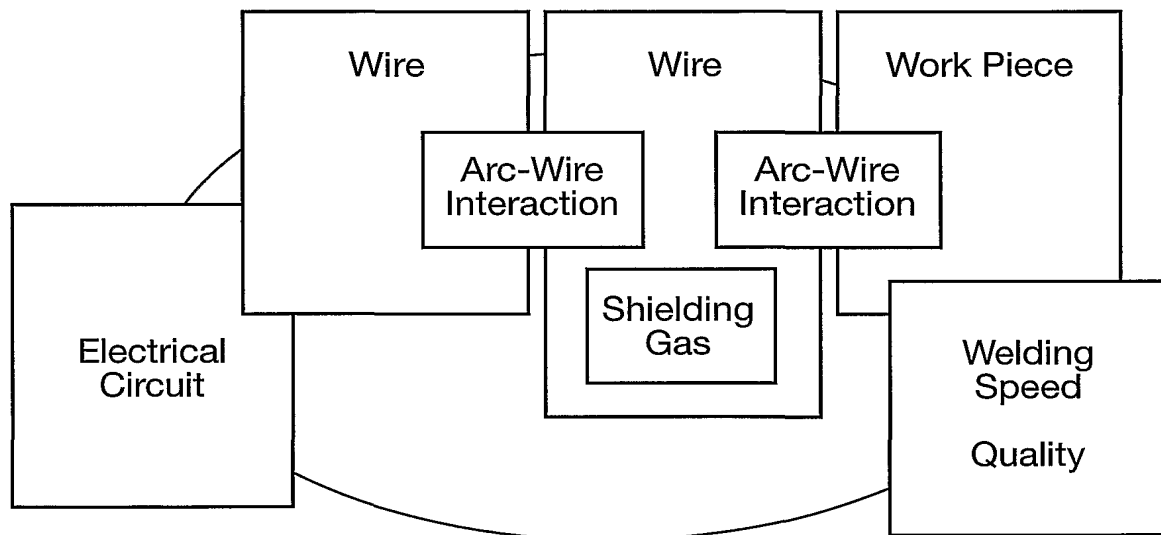
Fig. 8

Fig. 9

Fig. 5

5/11
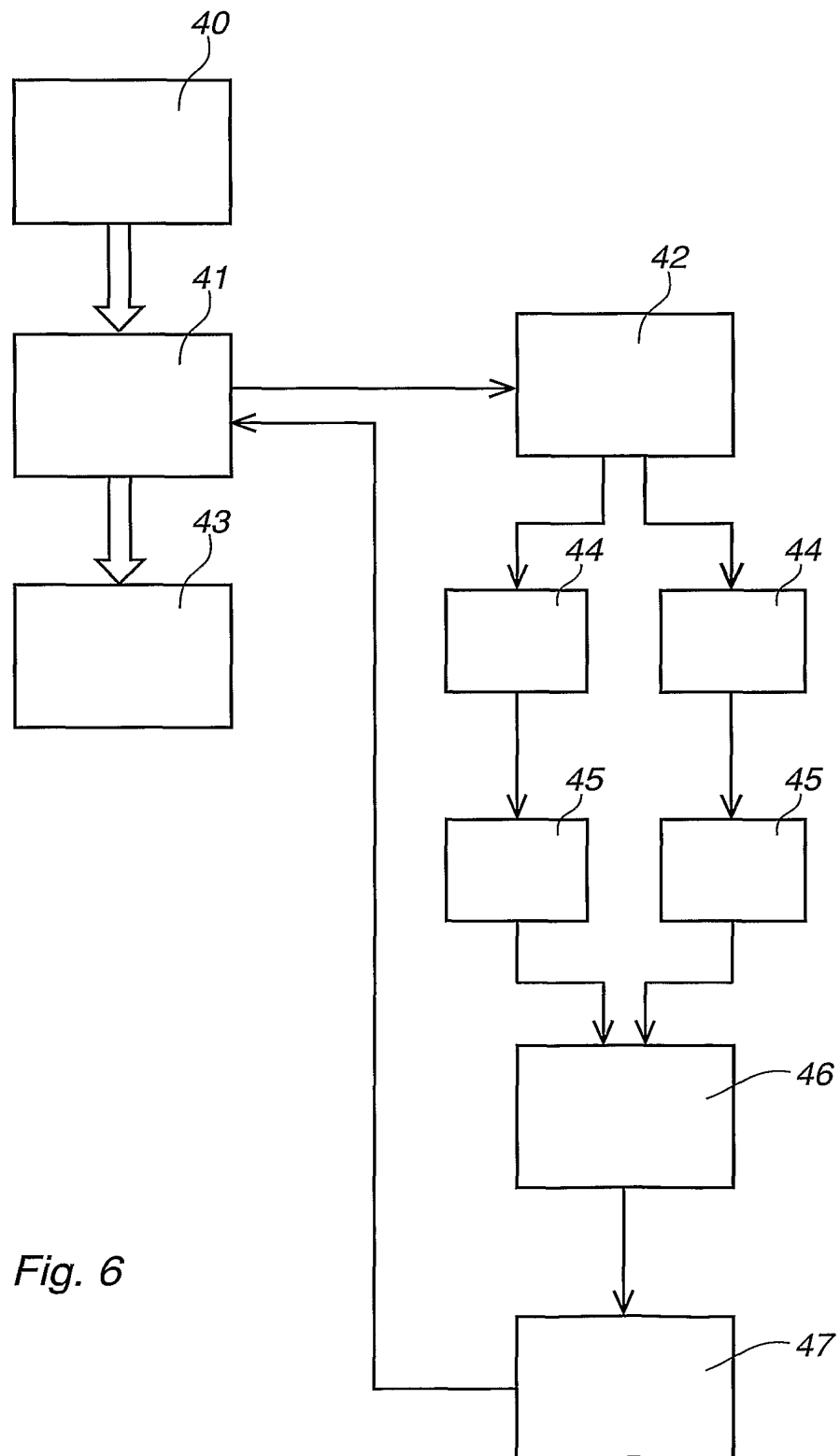
Fig. 6

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Fig. 6

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Fig. 10

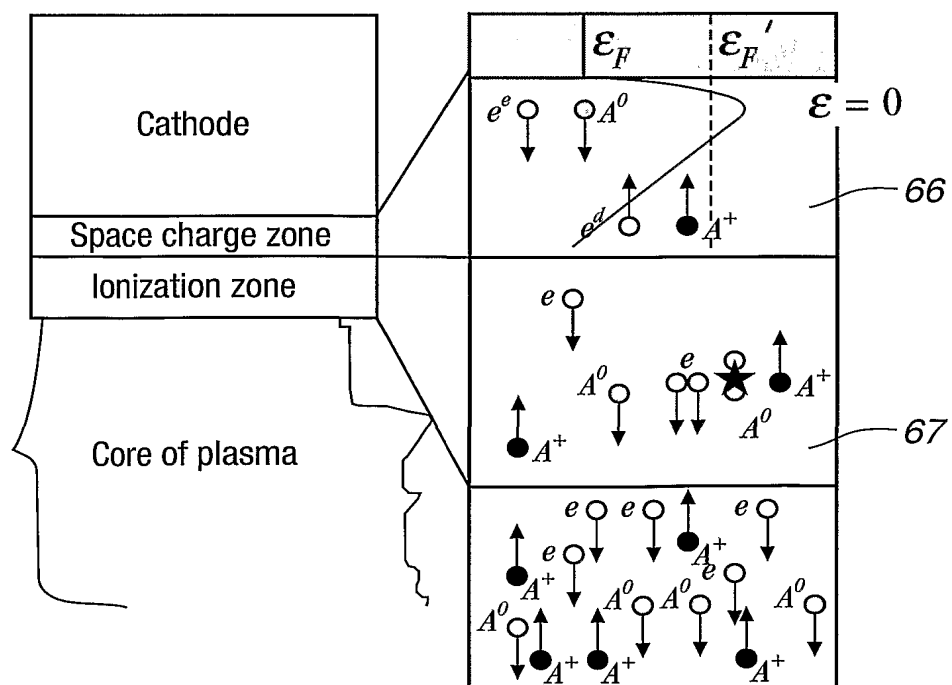
Fig. 11
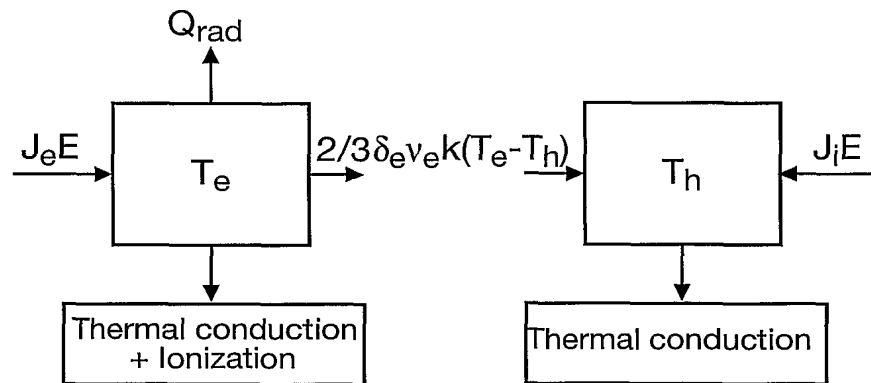
Q_{rad}

J_eE → | T_e | → $2/3\delta_e\nu_ek(T_e-T_h)$ → | T_h | ← J_iE

| Thermal conduction + Ionization | | Thermal conduction |

Fig. 12

Indirect Weld Parameters (IWPs)

Current
Voltage
Travel speed
Electrode feed rate
Electrode extension
Travel angle
Focused spot size
Depth of focus
Arc duration
Arc repetition rate
Beam power
...

Material Parameters (MPs)

Melting point
Thermal conductivity
Thermal diffusivity
Joint type
...

Direct Weld Parameters (DWPs)

Geometry:
  Bead width
  Penetration
...
Mechanical properties:
  Ductility
  Strength
...
Microstructure:
  Grain size
  Phase
...
Discontinuities:
  Porosity
  Incomplete fusion
...

Fig. 13

(C) $W_C^{(1)}$ (Mn) $W_{N_i}^{(1)}$ (Ni)

$\theta^{(1)}$ → $W_{Mn}^{(1)}$

$$h=\tanh(\Sigma w_j^{(1)}x_j + \theta^{(1)})$$

$$y=w^{(2)}h+\theta^{(2)}$$

(Bs) y

Fig. 15

- wire feed rate W_f
- arc length L
- heat transfer coef. h
- thermal conductivity k
- torch angle θ
- impact of droplets

...
- throat size of weld t3
- penetration δ_i

Fig. 14

Fig. 16

Fig. 17

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: B23K 9/095

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO INTERNAL, WPI-DATA, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0930125 A1 (AIR LIQUIDE CANADA), 21 July 1999 (21.07.99) --	1
A	WO 0102125 A1 (BECHTEL BWXT IDAHO, LLC), 11 January 2001 (11.01.01) --	1
A	US 6133545 A (YOSHIYUKI OKAZAKI ET AL.), 17 October 2000 (17.10.00) -- --------	1

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

*	Special categories of cited documents:
"A"	document defining the general state of the art which is not considered to be of particular relevance
"E"	earlier application or patent but published on or after the international filing date
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O"	document referring to an oral disclosure, use, exhibition or other means
"P"	document published prior to the international filing date but later than the priority date claimed

"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X"	document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y"	document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 July 2002	0 5 -08- 2002

Name and mailing address of the ISA/	Authorized officer
Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Magnus Westöö/AE Telephone No. +46 8 782 25 00

Form PCT/ISA/210 (second sheet) (July 1998)

Patent document cited in search report			Publication date	Patent family member(s)			Publication date
EP	0930125	A1	21/07/99	US	6051805	A	18/04/00
WO	0102125	A1	11/01/01	AU	6055700	A	22/01/01
				US	6236017	B	22/05/01
US	6133545	A	17/10/00	JP	3047890	B	05/06/00
				JP	11333563	A	07/12/99

PUB-NO: WO002078891A1
DOCUMENT-IDENTIFIER: WO 2078891 A1
TITLE: AN ARC WELDING METHOD
PUBN-DATE: October 10, 2002

INVENTOR-INFORMATION:

NAME	COUNTRY
KADDANI, AHMED	SE
WINDECKER, ULRIKE	SE
SKARIN, DICK	SE
LEMARINIER, PAVEL	SE
ZAHRAI, SAID	SE
GU, CHUN-YUAN	SE

ASSIGNEE-INFORMATION:

NAME	COUNTRY
ABB AB	SE
KADDANI AHMED	SE
WINDECKER ULRIKE	SE
SKARIN DICK	SE
LEMARINIER PAVEL	SE
ZAHRAI SAID	SE
GU CHUN-YUAN	SE

APPL-NO: SE00200648
APPL-DATE: March 28, 2002

PRIORITY-DATA: SE00101163A (April 2, 2001)

INT-CL (IPC): B23K009/095

EUR-CL (EPC): B23K009/10

ABSTRACT:

CHG DATE=20021101 STATUS=O>A method for controlling an arc welding equipment (21) used in a welding operation and adjustable by varying at least one welding parameter value, comprising the steps of determining said at least one welding parameter while using a theoretical model (24) of the welding process associated with the welding operation, and controlling the operation of the welding equipment and the welding process associated therewith by using said at least one welding parameter for adjusting the welding equipment and a device comprising an arc welding equipment (21) used in a welding operation and adjustable by varying at least one welding parameter and an arrangement (22) for controlling the operation of the arc welding equipment, said control arrangement including a means (23) adapted to determine the value of said at least one welding parameter while using a theoretical model (24) of the welding process, and a member (25) adapted to control the operation of the welding equipment and the welding process associated therewith by using said at least one welding parameter value for adjusting the welding equipment.